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AFRL/RZSA
10 E. Saturn Blvd.
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14. ABSTRACT
Without a constant force acting, all formation flying satellites are in orbits that contain the center of the Earth. Their orbits cross twice every period, and the satellites tend to converge on each other unless a continuous separation force counteracts this convergence. The magnitude of the separation force required is proportional to the total mass of the two spacecraft and their separation distance. In low Earth orbit, thrust forces between 100 and 1000 mN are required for satellites pairs with masses between 100 and 1000kg separated by 1km. This work evaluates momentum exchange through fluid streams as a means of maintaining side-by-side spacing between a pair of formation flying satellites. Droplet streams of very low vapor pressure silicone oil are generated on each spacecraft and projected through space to a receiving satellite. The receiving satellite collects the droplet stream and pumps the fluid to the droplet generator where a return stream is produced and sent back to the originating satellite. Therefore, tandem satellites could be envisioned as using streams of small silicon oil droplets continuously exchanged between them to produce the force required to maintain constant separation. This work addresses many of the perturbations in Earth orbit that can keep the droplets from their intended path between satellites.

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Constant Momentum Exchange Between Microspacecraft Using Liquid Droplet Thrusters

Thomas B. Joslyn[1]
United States Air Force Academy, USAF Academy, CO 80840

Andrew D. Ketsdever[2]
Air Force Research Laboratory, Propulsion Directorate, Edwards AFB, CA 93524

Without a constant force acting, all formation flying satellites are in orbits that contain the center of the Earth. Their orbits cross twice every period, and the satellites tend to converge on each other unless a continuous separation force counteracts this convergence. The magnitude of the separation force required is proportional to the total mass of the two spacecraft and their separation distance. In low Earth orbit, thrust forces between 100 and 1000 mN are required for satellites pairs with masses between 100 and 1000kg separated by 1km. This work evaluates momentum exchange through fluid streams as a means of maintaining side-by-side spacing between a pair of formation flying satellites. Droplet streams of very low vapor pressure silicone oil are generated on each spacecraft and projected through space to a receiving satellite. The receiving satellite collects the droplet stream and pumps the fluid to the droplet generator where a return stream is produced and sent back to the originating satellite. Therefore, tandem satellites could be envisioned as using streams of small silicon oil droplets continuously exchanged between them to produce the force required to maintain constant separation. This work addresses many of the perturbations in Earth orbit that can keep the droplets from their intended path between satellites. Although many significant perturbations were identified, no show-stopping effects were uncovered for this concept. Droplet streams are capable of providing several Newtons of thrust capable of separating satellites with an average mass of several thousand kilograms more than a kilometer apart.

I. Introduction

The research presented here evaluates momentum exchange through fluid streams as a means of maintaining side-by-side spacing between a pair of formation flying satellites. Droplet streams of very low vapor pressure silicone oil are generated on each spacecraft and projected through space to a receiving satellite. The receiving satellite collects the droplet stream and pumps the fluid to a droplet generator where a return stream is produced and sent back to the originating satellite to begin the process again. A conceptual drawing of the overall concept might look like Figure 1 in which two spacecraft are travelling in the horizontal direction while imaging the Earth. The side-by-side satellites use streams of small silicon oil droplets continuously exchanged to produce the force needed to maintain constant separation. This study investigated various aspects of generating and collecting such a droplet stream including the many environmental forces acting to disturb droplets from their intended path between satellites. These forces include drag, charging in the space environment, and the resulting electrostatic interactions between charged droplets. A material charging model called NASCAP was used to predict droplet charge levels in polar Earth orbit (PEO).

In the past decade, the advantage of satellite formations to the field of remote sensing gave rise to several proposals for their implementation. The first tandem satellite formation to fly will likely be a satellite pair called TarraSAR-X and Tandem-X. TarraSAR-X was launched in June 2007 to a nominal 514km altitude polar orbit. The companion satellite, Tandem-X, is expected to be launched in 2010. These satellites will provide the first bi-static synthetic aperture radar (SAR) platform in space. This technique is expected to provide topographic imaging resolution on the order of 1cm. [1] To achieve a side-by-side configuration, the Tandem-X formation utilizes two

[1] Assistant Professor, Department of Astronautics, AIAA Member.
[2] Senior Research Engineer, AIAA Associate Fellow.

offset polar orbits depicted in Figure 2. Because of the ever-changing separation distance between the Tandem-X/TerraSAR-X satellites, the formation does not produce uniform observations since is unable to achieve the same separation baseline over all parts of the Earth. A consistent baseline is important for certain missions where timely detection of surface changes is necessary.

Since tandem side-by-side satellites are each in orbits around the center of the Earth, their orbits cross twice every orbital period and they tend to converge on each other unless a continuous separation force counteracts this convergence. The magnitude of the separation force required is proportional to the total mass of the two spacecraft and their separation distance. Applying the Clohessy-Wilshire equations, preliminary work [2] has quantified the force required to maintain a constant satellite separation. In low-Earth orbit (LEO), 100 to 1000mN is required for two satellites with masses between 100 and 1000 kg, respectively to maintain a separation distance of 1km. Figure 3 shows the required thrust in a 600 km LEO orbit to maintain a constant separation of two satellites of equal mass. For comparison, the thrust that can be produced by an opposing set of liquid droplet streams of a given diameter and velocity are given in Figure 3 as well. [3] A range of formation separation distances between tens of meters to at least one kilometer would be useful to the remote sensing community.

Figure 1: Liquid Droplet Thruster concept for formation flying satellites.

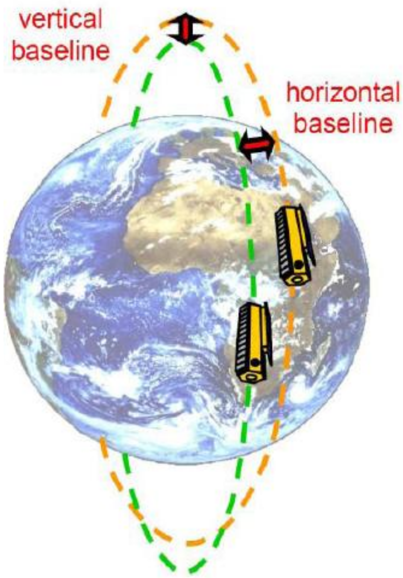

Figure 2: HELIX orbit configuration for Tandem-X and TerraSAR-X spacecraft. [1]

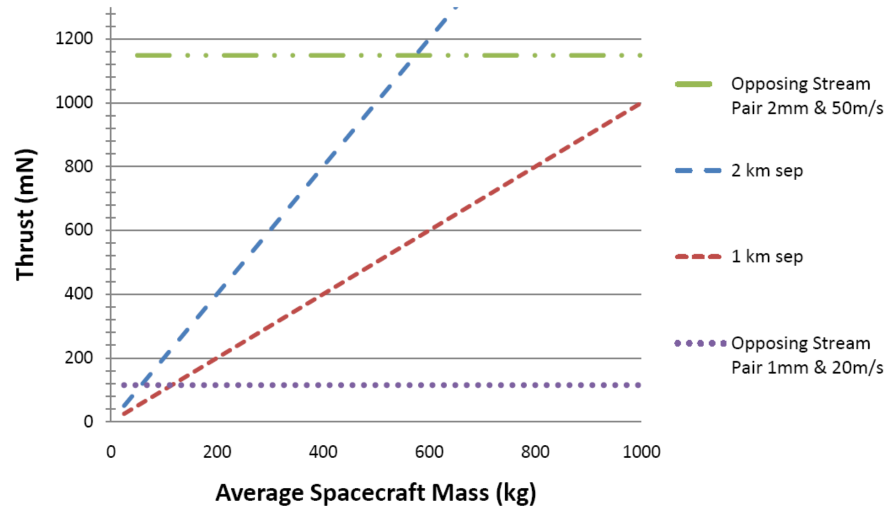

Figure 3: LEO (600km altitude) thrust required as function of spacecraft mass. Thrust produced by opposing streams highlighted.

In this study, droplet streams were investigated that are capable of providing several Newtons of thrust when travelling at stream velocities demonstrated in past droplet stream studies. [4-7] Such streams generate the necessary momentum transfer with a single pair of droplet streams to provide two 3000 kg LEO satellites with one kilometer separation. Polar orbit is both a desirable place to fly remote sensing satellites in formation and a challenging environment to perform droplet transfer due to dramatic changes to the auroral plasma charging environment during periods of high geomagnetic activity. A focus of this study is on obstacles to using the concept in LEO and PEO. This study focuses on the effects of drag in LEO and droplet charging in PEO.

II. Results

Several effects were investigated to assess the viability of the liquid droplet thruster concept for formation flying satellites. Different environmental factors are important in various operational regimes. For example, the effects of the vacuum environment of space required a careful selection of candidate droplet liquids that have extremely low vapor pressures. Specifically for operation in LEO, drag was considered a major impediment to the implementation of this concept. However, in PEO, droplet charging was identified as the major environmental interaction. An assessment of these droplet-environment interactions is given below.

A. Liquid droplet fluid selection and droplet formation

Droplet streams in space were first proposed in the 1980s to facilitate the radiation of waste heat on large space structures like power generating satellites and the space station. [4-7] The National Aeronautics and Space Administration (NASA) and the United States Air Force (USAF) funded the Liquid Droplet Radiator (LDR) program that demonstrated feasibility of droplet streams and developed technologies for generating and collecting them in space. Many of the technologies developed for the LDR program would be equally useful for droplet stream propulsion.

Many types of low vapor pressure fluids were considered for use in a droplet stream propulsion system. LDR researchers considered the fluids in Table 1, and the fluid selected by NASA and the USAF in the 1980s was trimethyl pentaphenyl siloxane which is a silicon based oil known best by its trade name Dow Corning 705 (DC705). [8] This fluid has a low vapor pressure and relatively low viscosity at nominal satellite operating temperatures. Low viscosity is advantageous because it allows droplet stream production at a lower reservoir pressure. Other fluids considered include another silicone oil called DC704 and a synthetic hydrocarbon called Neovac SY. Both fluids are desirable for their relatively low viscosity, and low vapor pressure.

Fluid	Vapor Pressure (Torr)	Molecular Weight (amu)	Viscosity (centistokes)
DC705	3×10^{-10}	546	175
Fomblin Z25	3×10^{-12}	9500	355
Krytox 16256	3×10^{-14}	11000	2560
Krytox 1502	6×10^{-7}	1465	17

Table 1: Properties at 20°C of candidate fluids.

DC704 and DC705 have similar density: 1070 kg/m^3 for DC704 and 1097 kg/m^3 for DC705. The fluids differ chemically by a single methyl group, which is replaced by a fifth Benzene ring (C_6H_6) in DC705 as seen in Figure 4. Previous research shows that charging properties of DC704 and DC705 are very similar. [9] For these reasons, much of the research presented in this report is quite applicable to both DC704 and DC705.

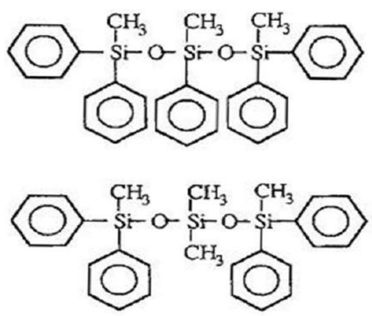

Figure 4: Chemical structure for DC705 and DC704. [3]

As seen in Figure 5, the vapor pressure of silicone oils, and other fluids considered, increases significantly as a function of temperature. As a result, DC705 is only practical for use at temperatures below 350K. For most spacecraft, this temperature limit is quite reasonable. Indeed, one of the advantages of having fluid on-board is the flexible temperature control it affords the spacecraft through active control of fluid flow and by using the propulsion system itself as a liquid droplet radiator. In other words, the liquid droplet thruster system could also have the added benefit of acting as a thermal control system.

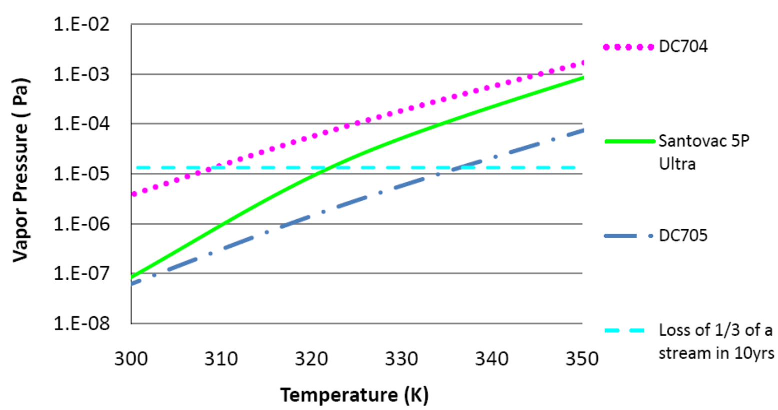

Figure 5: Vapor pressure as a function of temperature for candidate fluids.

It is necessary to break up a fluid column into uniform droplets to prevent randomly sized droplets from forming due to the tendency for a fluid column to minimize its surface area. This phenomenon, called Rayleigh instability, causes breakup into droplets of random size at about 3 stream diameters from the producing orifice. [10] Droplets of varying size are affected differently by drag and other forces described in this study resulting in a very large impact region at the receiving satellite, making collection difficult. Droplet generators developed for the LDR program were based on vibration-induced breakup of a fluid column in to droplets. This mature technology was first pioneered by Lord Rayleigh in the 19th century.

Micro-solenoid valves are a proposed new method of droplet generation. This technology was developed in the decade following NASA and USAF cancellation of the LDR program. These valves can operate for several million cycles and are capable of generating a droplet stream for 3-5 years. Two types of micro-solenoid valves were tested in this study and were found to produce droplet streams of sufficient uniformity, size, and speed to satisfy requirements of systems envisioned. When compared to piezoelectric droplet generators, solenoid generators have less fluid loss at startup and shutdown and can produce droplets with any desired gap distance between droplets (assuming relatively large operating frequencies). Larger gaps between droplets would act to reduce the electric field strength between charged droplets that would otherwise cause dispersion of transiting droplets from the direct path between satellites.

Of course systems which operate on solid particles (e.g. BB's) could also be envisioned where losses due to vapor pressure would not be significant. In this study, the ease of collecting and transporting within the spacecraft a liquid was assumed to be advantageous. Another advantage is storage density of the liquid propellant. Although solid propellant has a larger storage density, the overall propellant volume might be larger due to solid particle packing efficiency. An overall systems study needs to be performed to assess the advantages and disadvantages of both liquid droplet and solid particle propulsion concepts.

B. LEO Drag

Drag can be significant at orbital altitudes below approximately 600km. Because of the very low ballistic coefficient for small droplets, drag slows droplet orbital velocity much more than it does the orbit velocity of satellites. In this way, drag alters the trajectory of transiting droplets and can result in droplets straying 10cm or more from a direct path between satellites as shown in Figure 6 for an orbital altitude of 300km. [3] The amount of droplet drift caused by drag will vary with atmospheric density that is a function of altitude, solar cycle, and geomagnetic activity. Increasing the size or density (i.e. increasing the ballistic coefficient) of droplets helps reduce the magnitude of drift due to drag. The direction and magnitude of drag force is relatively predictable and can be compensated for by projecting a stream that leads the target collector sufficiently. A droplet stream pointing control system will require a feedback sensor that can detect droplet impact location. Drag effects on droplets is a compelling reason to operate the liquid droplet thrusters (and thus, tandem formations of satellites) at altitudes above 600km.

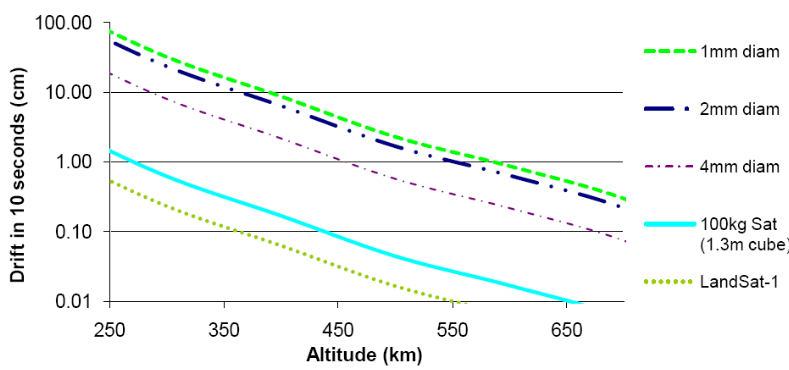

Figure 6: Drift from centerline due to drag at 300km altitude for a 10s transit time. Solar maximum conditions assumed.

C. PEO Charging

As silicon oil droplets move through space they come into contact with ambient electrons and ions that constitute the Earth's plasma environment. Free electrons in near-Earth space move in all directions at very high speeds that are about 200km/s, more than an order of magnitude higher than orbital velocities. Consequently, electrons impact orbiting bodies from all directions as depicted in Figure 7. In contrast, positively charged ions in near-Earth space have an average velocity magnitude ($\bar{v}$) of only about 1km/s. This is significantly slower than orbit velocity, and ions tend to hit the ram side of orbiting bodies much more frequently than the wake side. The velocity of electrons is about two orders of magnitude greater than that of ions and the resulting flux of electrons to the surface is up to 50 times greater than the flux of ions to the surface.

An object in space is exposed to many different processes that add or remove electrons at the surface. Determining the net current at the surface of an object is a matter of determining and then summing the current due

to each of these processes. Quantifying net current is complicated by the fact that the processes that add or remove electrons from the surface are also influenced by the surface charge. Secondary electrons with sufficient kinetic energy to escape in one instant may be retained by a more positively charged surface in the next. Consequently, the most accurate charge determination algorithms are iterative, solving for the charge density and potential of the elements of a mesh of small volumes for a time step and then repeating the process for the next time step. Mathematically, the current balance for a droplet at a floating electrostatic potential (*V*) is expressed by

$$I_{net}(V)= I_e(V)- [I_i(V)+ I_{se} (V)+ I_{si}(V)+ I_{bse}(V)+ I_{ph}(V)] \quad (1)$$

where I_e is the incident electron current on the surface, I_i is the incident ion current, I_{se} is the secondary electron current caused by the incident electrons, I_{si} is the secondary electron current caused by the incident ions, I_{bse} is the backscattered incident electrons, and I_{ph} is the secondary electron current caused by incident photons.

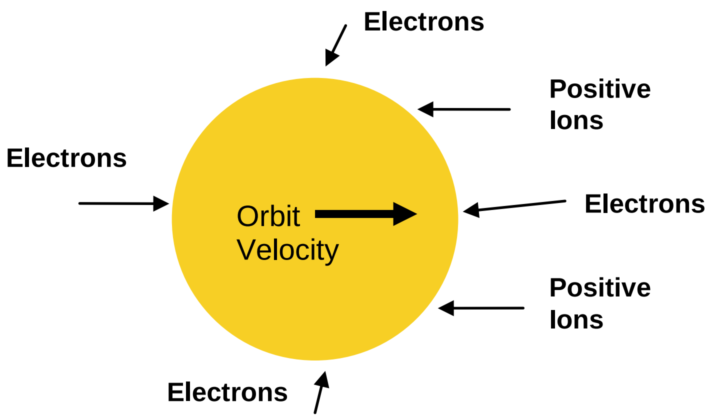

Figure 7: Charging sources in Earth's plasma environment.

The potential in the plasma near a charged surface *V* is given by the Poisson equation. [11] The computer based charge simulation code; NASCAP solves this equation by applying the specified environment flux distribution electron and ion densities in an iterative process while developing the sheath at the surface and recalculating the particle densities accordingly. One advantage this gives NASCAP, over other charge modeling codes, is its ability to calculate accurate electric fields in the surrounding plasma. [12] NASCAP employs the Boundary Element Method as developed by Brebbia [13] as a means for relating fields and potentials in the surrounding plasma to sources at the surface. This method allows rapid determination of changes in plasma densities, current flow to/from the surface and a new solution to Poisson's equation to determine changes in electrostatic potential that occur during the time step. Environmental conditions based on data from the Defense Meteorological Satellite Program (DMSP) were used in NASCAP.

Analysis of auroral charging of silicon droplets was done using environment data from DMSP spacecraft between 500 and 800km. The analysis shows that the charge will remain between -26V and +21V in and out of eclipse. A sample calculated potential is shown in Figure 8. Equilibrium potential is reached within 0.2 seconds without any significant overshoot of equilibrium potential in either sun or eclipse. Negative charging due to electron deposition and secondary electron production is rapid but is then mitigated by low-energy ions within half of a second.

Figure 8: DC705 charging in DMSP (PEO) sunlit environment with elevated geomagnetic activity.

A simulation was conducted to quantify the effects of a droplet transitioning from eclipse to sunlight in a strong auroral charging environment as shown in Figure 9. All surfaces charge negatively in eclipse with leading hemisphere surfaces assuming a more positive charge. Following solar exposure at 0.15 seconds, surface elements on the sun facing side rapidly charge positive with very little overshoot and then equilibrate to a nearly neutral potential. Interestingly, the most negative elements on the anti-solar hemisphere briefly charge more positive before returning to a potential near that of equilibrium eclipse. It is believed that this positive charging on the anti-sun side occurs because positive ions in the plasma sheath on the sunlit side are repelled by the, now positive, sunlit surface charge and migrate to the anti-sun side where ion deposition occurs.

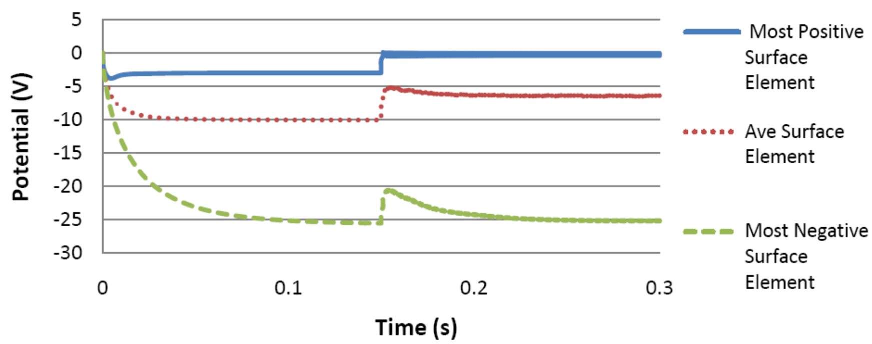

Figure 9: Transition from eclipse to sunlight in a strong 800km altitude auroral charging environment.

Table 2 summarizes the results of more than a hundred NASCAP simulations of DC705 droplets in various environments. Shielding of high-energy particles by Earth's magnetic field and the presence of high numbers of low energy plasma particles makes low latitude LEO the most benign environment to operate in. Droplet charge potentials remain less than 2.1 V despite high geomagnetic activity both in eclipse and in sunlight.

Environment:	**LEO**	**<800km Auroral (DMSP)**	**1500km Auroral (FREJA)**	**GEO**
Low Geomagnetic	**+0V , -0.5V (sun, eclipse)**	**+1.5V, -2V**	**+2V, -14V**	**+18V, +1.5V**
Nominal Geomagnetic	**+0V , -1V**	**+4V, -16V**	**+6V, -25V**	**Not Analyzed**
High Geomagnetic	**+2V , -2V**	**+21V, -26V**	**Insufficient Data (3 years only)**	**-2kV, -13kV**

Table 2: Summary results for equilibrium charging potentials in various orbits (maximum sunlit surface and minimum eclipse surface values).

DC-705 droplets were analyzed for their potential to break apart when exposed to significant charge levels. Droplet charge can be expressed as a function of voltage potential and droplet capacitance. Capacitance is directly proportional to droplet diameter and charge is directly proportional to capacitance so, for a given equilibrium voltage potential, larger droplets have greater charge. However, larger droplets also have greater surface tension forces holding them together than smaller drops. The increase in surface tension force with size is greater than the increase in Coulomb repulsion forces caused by the increase in droplet charge. Therefore, larger droplets can withstand greater voltage potential before breaking up. Droplets with a relative potential of 300 volts that are smaller than a millimeter in diameter will tend to break apart. Since the maximum anticipated charge potential on droplet surfaces in low altitude (<800km) polar orbit is less than 26 volts, breakup of droplets due to electrostatic self-interaction is not likely. The minimum DC705 droplet diameter required to prevent breakup at 26 volts charge potential is less than one micron (0.0055 mm).

Without charging, the dispersion of droplet impact from centerline is primarily caused by the scatter associated with the droplet formation at the generator. Using a Monte Carlo approach to the statistical scatter from a typical generator [5], 5000 simulated uncharged droplets impacted no more than 3mm from the collector's center after 50 seconds of travel. When droplets are uniformly charged electrostatic dispersion from stream centerline results in a ring shaped impact region at the droplet collector like the one depicted in Figure 10. The impact ring shown was created by simulating the transit of two-millimeter droplets each charged to a +100V potential. The circle depicted in the figure has a radius that is three standard deviations from centerline, large enough to collect 99.7% of transiting droplets. By choosing an acceptable percentage of collected droplets, a corresponding standard deviation can be determined and the collector sized accordingly. For the example shown, a collector 60cm in diameter fails to collect about 30 droplets in 5 years while a 70cm collector only loses one droplet in 5 years.

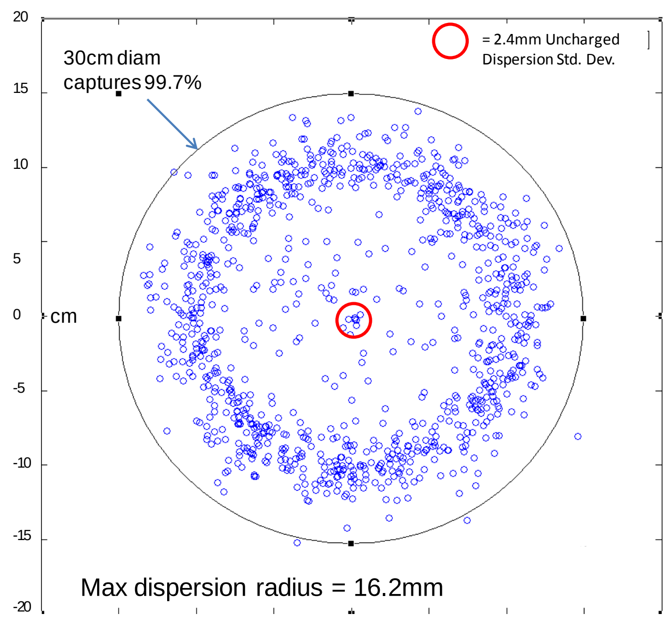

Figure 10: Charged droplet impact point after 50s transit time for 2mm droplet diameter. Each droplet charged to +100V potential.

III. Conclusions

This report has presented the results of a study of a new concept in satellite propulsion that relies on momentum transfer through projection of droplet streams through space. Analyses of various aspects of the concept have found no show-stoppers for the concept; however, the implementation of the concept requires a considerable amount of additional work. As a distinct advantage, a conceptual droplet thruster system would weigh about one-fifth as much as a comparable ion engine and consume about 1000 times less power. The relatively low required operating power of droplet stream propulsion effectively makes it an enabling technology for side-by-side tandem formation satellites. In addition, a droplet stream propulsion system contains most of the components needed in a LDR. Many components such as collectors and pumps were developed and tested as part of the LDR program and are well suited to droplet stream propulsion without modification.

The amount of off-course drift that droplets experience due to drag is affected by droplet diameter and speed that can be chosen to minimize off-course drift of droplets. Charging in PEO was found to be somewhat benign even during increased geomagnetic activity. The level of charging was found to be acceptable from the standpoint of unwanted droplet breakup due to Coloumb repulsion. The major influence of both drag and charging on liquid droplets was found to be in the design of the collecting system on the opposing spacecraft. Relatively large collecting diameters and reasonable pointing control are required for this concept to be viable.

Acknowledgments

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References

1. Zink, M., Krieger G., Fiedler H, and Moreira L., The TanDEM-X Mission: Overview and Status, Proceedings of the Geoscience and Remote Sensing Symposium, IEEE International, pp. 3944-3947 (23-28 Jul 2007).
2. Tragesser, S., Static Formations Using Momentum Exchange Between Satellites, J. Guidance, Control, and Dynamics, Vol. 32, pp. 1277-1286 (2009).
3. Joslyn, T., Charging Effects on Fluid Stream Droplets for Momentum Exchange Between Spacecraft, PhD Dissertation, University of Colorado, Colorado Springs (18 Nov 2009).
4. Totani, T., Kodama, T., Nagata, H., Kudo, I., Thermal Design of Liquid Droplet Radiator for Space Solar-Power System, Journal of Spacecraft and Rockets, Vol. 42, No. 3 (2005).
5. Muntz, E., M. Dixon, Applications to Space Operations of Free-Flying, Controlled Streams of Liquids, Journal of Spacecraft, Vol. 23, No. 4 (1986).
6. Mankamer, M., Snyder, R. Taussig, R., Liquid Droplet Radiator Systems Investigation, Air Force Rocket Propulsion Lab Techical Report, AFRPL TR-85-080, (Nov 1985).
7. White, K. Liquid Droplet Radiator Development status, AIAA Paper 87-1537 (Jun 1987).
8. Comparison of Diffusion Pump Fluids. Varian Inc., Available on-line: http://www.varianinc.com/cgi/bin/vacpower?cc1=110&cc2=162&classcode3=689&cid=KNNMNPKNFO [accessed 1 Apr 2010].
9. Issikawa, K., K. Goto, Secondary Electron Emissions from Diffusion Pump oils I, Japanese Journal of Applied Physics, Vol. 6, No. 11(1967).
10. White, F., Fluid Mechanics, 6th Ed. McGraw Hill, (2009).
11. Chen, F., Introduction to Plasma Physics, Harper Press, Chicago (1984).
12. Hastings, D., Garrett, H., Spacecraft Environment Interactions, Cambridge University Press (1996).
13. Brebbia, S., Boundary Element Methods, Springer Verlag, New York (1981).